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The evolving disk galaxy population

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Abstract. In this contribution, I present a simplified overview of the evolution of the disk galaxy population since $z = 1$, and a brief discussion of a few open questions. Galaxy evolution surveys have found that the disk galaxy population forms stars intensely at intermediate redshift. In particular, they dominate the cosmic star formation rate at $z < 1$ — the factor of ten drop in cosmic average comoving star formation rate in the last 8 Gyr is driven primarily by disk physics, not by a decreasing major merger rate. Despite this intense star formation, there has been little change in the stellar mass density in disk galaxies since $z = 1$; large numbers of disk galaxies are being transformed into non-star-forming spheroid-dominated galaxies by galaxy interactions, AGN feedback, environmental effects, and other physical processes. Finally, despite this intense activity, the scaling relations of disk galaxies appear to evolve little. In particular, as individual galaxies grow in mass through the formation of stars, they appear to grow in radius (on average, the population grows inside-out), and they appear to evolve towards somewhat higher rotation velocity (i.e., mass is added at both small and large radii during this inside-out growth).

1. Introduction

The properties and evolution of the disk galaxy population are a critical diagnostic of the galaxy formation process in a dark matter-dominated Universe. Galaxy disks, formed naturally as a result of a collapse in which at least some of the angular momentum is conserved (Fall & Efstathiou 1980), are relatively fragile beasts. Interactions with low-mass halos are likely to thicken the stellar disk (e.g., Toth & Ostriker 1992; Benson et al. 2004) and/or lead to warps and lopsidedness; interactions with galaxies/halos with masses within a factor of a few of the galaxy mass look likely to disrupt the stellar disk entirely (e.g., Koda et al. 2008). Thus, the evolution and properties of the disk galaxy population are not only a fascinating puzzle in their own right, but also give insight into those environments which are the least affected by the characteristic pummeling that galaxies in Λ CDM seem to receive.

In the seven years since the first Vatican disk galaxies meeting, a number of the basic observational features of the evolution of the disk galaxy population have come into place. In this contribution, I present a brief overview of what I consider to be some of the most important features of the evolution of the disk galaxy population since $z = 1$ (roughly the last 7-8 billion years), and pose a few questions that I had after this conference. These features fall under three broad themes: star formation in disks, stellar mass in disks, and disk galaxy scaling relations. In what follows, in the spirit of a review, I will deliberately

over-simplify the observational results somewhat in order to clarify the three basic messages of this contribution.

2. Star formation in disks

As a community, we have made excellent progress towards understanding the contribution of disk galaxies to the star formation census of the cosmos, especially since $z = 1$. While clearly much work remains to be done, I would maintain that the bottom line is clear: since $z = 1$, the majority of all stars that form do so in galactic disks (see, e.g., Hammer et al. 2005; Bell et al. 2005; Wolf et al. 2005; Melbourne et al. 2005, and Fig. 1).

While this bottom line, I think, is clear, there are a number of issues with current observational studies which need to be understood and improved upon. The key issue is that identifying disks unambiguously is not straightforward: does one do this using a cut in light profile concentration, Sersic Index (essentially selecting galaxies with light profiles not that different from an exponential), using visually classified disks, or by splitting by rest-frame color into blue cloud and red sequence? Workers in this field have taken a number of different approaches, and it is a testament to the robustness of the result that independent of approach it is clear that the bulk of star formation is in disks. Yet, in order to understand this result in depth, more refined approaches will be necessary. Furthermore (as I will touch on later), there are observational selections (in photoz or spectroscopic z studies) that favor the detection of low mass galaxies with preferentially high SFRs; such a selection will skew our understanding of the population average. Finally, high-quality SFR estimates from far-IR SEDs will come into place in the next years with the upcoming launch of *Herschel*.

The following is an incomplete list of a few implications of this result.

- Disk galaxies are forming stars vigorously at intermediate redshift. In the particular case of massive galaxies, star formation happens at rates typically high enough to allow them to double their mass in just a few Gyr (Noeske et al. 2007a,b; Zheng et al. 2007).
- The fact that most of the star formation is in disks at $z < 1$ makes it clear that most of the star formation is *not major merger-driven*. Jason Melbourne and coworkers presented a poster at the meeting in which they argued for an even stronger statement — they found in deep imaging of star-forming disks relatively little evidence for preferentially more minor merging/accretion in intensely star-forming systems relative to non-star-formers (although Hammer et al. 2007 have a different view, based on disturbed velocity fields in a significant fraction of intermediate redshift LIRGs).
- Thus, the drop in the cosmic SFR from $z = 1$ to the present day is due primarily to ‘quiescent’ processes, e.g., gas consumption (the consumption of gas that the galaxy already has) and/or a reduced rate of accretion of fresh gas from the cosmic web (either through cooling from a hot medium or from direct accretion).

Given these implications, there are a few questions that would be great to have understood in more detail:

- Estimates of star formation history in the solar cylinder tend to come up with a roughly constant SFR since the formation of the disk. Study of the evolution of the SFR of the disk galaxy population since $z = 1$ suggest at least factors of several higher SFR 7-8 Gyr ago, on a global scale. It will be an important challenge for the community to ‘close the loop’, and to verify (or rule out!) that the global SFR of the Milky Way was significantly higher in the past, and that one expects to infer a \sim constant SFR at ~ 3 disk scale lengths (where dynamical re-arrangement of stars after they form may play an important role here; see, e.g., the contribution of Debattista and Roškar; Roškar et al. 2008).
- From work with high velocity HI clouds, there is the suggestion of an infall rate of a few tenths of a solar mass per year of new gas (Putman, this conference; Peek et al. 2008); this is less than half of the current SFR. It will be an important challenge to better measure the infall rate today, and better constrain the infall history of disk galaxies in a general sense. This is a field in which there is excellent promise, as it is an ideal arena for the synthesis of observations of SFRs, metallicities (and metallicity histories), and gas contents (especially with ALMA) with simulations of disk galaxy evolution in a cosmological context.
- It would appear that the *average* specific SFR of low-mass galaxies ($\leq 10^{10} M_{\odot}$ in stars) at intermediate redshifts is very high (doubling times are typically 1 Gyr; see Fig. 2 of Zheng et al. 2007). I am sure that this is naive observer-speak, but I am always troubled by an *entire population*, and not a small one, which appears to be star forming itself out of existence. There are simply not enough high mass galaxies around to represent the end-products of this intense star formation. I suspect that our census of low mass objects at intermediate redshifts is very biased towards only those galaxies with high SFRs. If incompleteness really is the problem, rectifying this situation will not be straightforward, and will require a dedicated near-IR photoz effort (to reduce the effects of star formation on the observed luminosities) followed by deep and determined spectroscopy (to verify the often unreliable photozs of very faint objects).

3. Stellar mass in disks

An obvious implication of the above discussion is that we should expect to see a huge increase in the stellar mass density in disks since $z = 1$ — they are forming stars like crazy; they have to go somewhere (see the predicted mass growth in blue galaxies – dotted line in the middle panel of in Fig. 1)!

The last years have seen the creation of a number of datasets with which one can estimate the stellar mass function of disks (bearing in mind the obvious issue of ‘What is a disk?’ that was brought up in the last section). The key result of these studies is that there has been *very little evolution* in the mass density

in disk-dominated (or blue cloud¹) galaxy population since $z = 1$. Instead, one sees the stellar mass density of non-star-forming (primarily bulge-dominated) galaxies growing by factors of two or more in that period of time (e.g., Bell et al. 2004b; Brown et al. 2006; Faber et al. 2007; Bell et al. 2007, and Fig. 1)².

The implication of this is clear, and profound. There are physical processes which are turning off star formation in a significant fraction of star-forming disk galaxies, and leading to the creation or augmentation of a bulge. This is not a subtle process, as it has affected $\sim 1/2$ of the stellar mass density which either was on, or formed in, the blue cloud.

There are a number of possible physical processes that are likely to play a role: e.g., galaxy merging (to create bulges), AGN feedback (to evacuate the gas, or prevent it from cooling at late times), stripping of gas in group/cluster environments, and tidal stripping/harassment in dense environments. A key issue for the community in the future is to identify and explore the relative importances and roles of these processes on shaping the evolving disk galaxy population.

4. The evolution of galaxy scaling relations

OK, where are we? We've seen that disk galaxies form stars intensely since $z = 1$. We've seen that many disk galaxies are transformed into non-star-forming spheroid-dominated galaxies since $z = 1$. There has been intense activity in the disk galaxy population since $z = 1$ — it would be reasonable to expect some signature of the physics of this intense activity imprinted in the galaxy scaling relations.

While there is much work left to do, I would maintain that we have a basic understanding of the evolution of the stellar mass Tully-Fisher relation (the stellar mass–rotation velocity relation) and the stellar mass–radius relation. It would appear that neither relation changes appreciably since $z = 1$ (e.g.,

¹A selection for blue cloud galaxies is often made in this game, because the surveys which have enough volume to measure the relatively subtle changes in the stellar mass density were not large enough to have HST imaging covering their entirety. Thus, blue cloud is often selected, noting that almost all blue cloud galaxies are disk dominated (e.g., Bell et al. 2004a).

²For those who are more empirically-minded, the observable result goes as follows. The rest-frame B -band luminosity function evolves by roughly 1 magnitude in L^* (putting it in terms of a Schechter function fit to the luminosity function) since $z = 1$ for both red and blue galaxies. The density normalization ϕ^* remains basically unchanged for blue galaxies, whereas for red galaxies it appears to have increased by roughly a factor of 2 or more; the end result is that the luminosity density in blue disks was 2.5 times higher at $z = 1$ than today, and the luminosity density in red early-type galaxies remains basically unchanged from $z = 1$ to the present. In this time, both red and blue galaxies have reddened considerably (because the stars in these galaxies have aged from $z = 1$ to $z = 0$). It is unavoidable that as the population ages and becomes redder that it should fade also. The predicted fading (from stellar population models) for both red and blue galaxies is roughly ~ 1 mag since $z = 1$ (corresponding more or less to the observed shift in L^* ; i.e., the knee in the stellar mass function does not shift appreciably since $z = 1$). Thus, the stellar mass density in blue disks appears to remain more or less constant since $z = 1$, whereas red early-types appear to double or more in mass density — in both cases, this result is driven by the changes in ϕ^* rather than changes in the basically non-evolving knee of the stellar mass function M^* .

Barden et al. 2005; Conselice et al. 2005; Trujillo et al. 2006; Flores et al. 2006; Kassin et al. 2007).

These are key observational results, as they place significant constraints on the evolution of galaxies:

- Disk galaxies appear to evolve *along* the stellar mass–radius relation. They are forming stars, therefore they are growing significantly in stellar mass since $z = 1$. Thus, the population must be growing in radius as the population builds up mass (in order to stay on the scaling relation) — the population is on average growing inside-out (Barden et al. 2005; Trujillo et al. 2006).
- Disk galaxies appear to also evolve *along* the stellar mass–rotation velocity relation. Thus, as they grow in stellar mass they also grow in rotation velocity. This is an interesting constraint. The measured rotation velocity is set by the dark and luminous matter content within roughly 2 half-light radii. If galaxy mass is added at *only* large radii (i.e., really inside-out growth), one would expect rotation velocities to change little as the galaxy gains mass. Thus, the non-evolution of the stellar mass Tully-Fisher relation shows that galaxies are adding mass at all radii (affecting the rotation velocity), while making sure to preferentially add it at large radii (to ensure inside-out growth).

Models of galaxy formation which are able to start interpreting such phenomenologies are emerging (e.g., Somerville, this conference; Somerville et al. 2008), and will help to both sharpen our understanding of the evolution of the disk galaxy population, and motivate improved analyses of new datasets.

5. Conclusions and discussion

In this contribution, I have presented an over-simplified view of the evolution of the disk galaxy population:

- Disk galaxies form stars intensely since $z = 1$. They dominate the cosmic average SFR since $z = 1$; the factor of 10 decline in cosmic SFR since $z = 1$ is primarily driven by disk galaxy physics (gas consumption, decreased accretion from the cosmic web), not changes in the galaxy merging rate.
- Despite this intense star formation, the disk galaxy population does not grow in mass since $z = 1$. Large numbers of star-forming disks are being transformed into non-star-forming spheroid-dominated galaxies.
- As disk galaxies gain mass through star formation, they grow in radius (i.e., the population grows inside-out) and rotation velocity (i.e., mass is added at small and large radii during this inside-out growth).

A final word. This picture of a dynamic disk galaxy population has important implications for how we interpret the results of our observations. Statements such as ‘massive disk galaxies are in place at $z = 1$ and appear to evolve little to the present day’ are incorrect. Some of these massive disk galaxies have become

bulge-dominated at the present day (and are therefore not in the $z = 0$ control disk galaxy sample), some are in (rare) even more massive disk galaxies. This has implications for how one should interpret a variety of observations: bar fractions, metallicity–mass relations, mass–radius and mass–rotation velocity relations. While some studies specifically address such issues (e.g., Kassin et al. 2007), it is important to bear the (observed!) dramatic evolution of the disk galaxy population in mind when interpreting scaling relations and properties of the evolving disk galaxy population.

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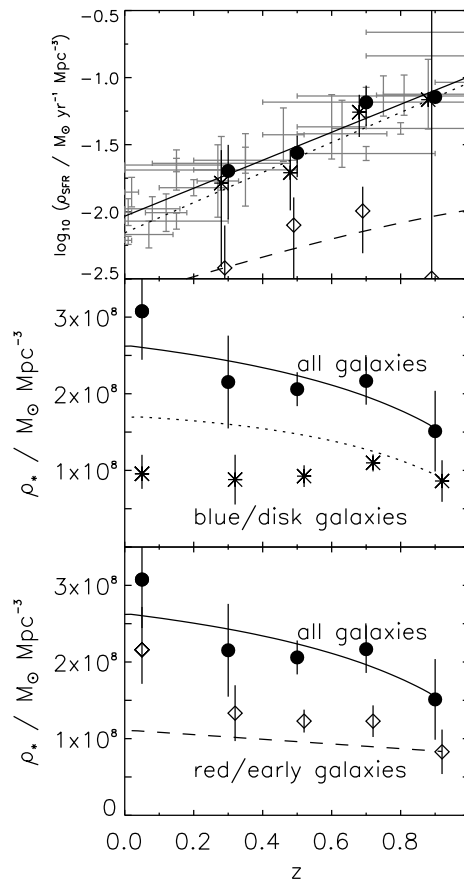


Figure 1. **Top:** The cosmic SFR history since $z = 1$ for all galaxies (filled circles and a compilation of literature values in gray). The contribution from blue cloud (primarily disk galaxies) is shown as asterisks. The red sequence contribution (mostly early-type galaxies with no star formation – the star formation is from a mix of mergers and edge-on spirals) is shown as diamonds. **Middle:** The filled circles show the stellar mass evolution predicted from the cosmic SFR (solid line) along with observations from Borch et al. (2006). Since almost all star formation is in blue (primarily disk) galaxies, the predicted growth in stellar mass in the blue galaxy population is substantial (dotted line); there is no observational evidence for such a mass growth (asterisks). **Bottom:** Instead, all observed mass growth is in red sequence (primarily early-type) galaxies (diamonds; almost no growth is predicted as shown by the dashed curve). Adapted from Bell et al. (2007).